Final Technical Report

External Grant Award Number:
G16AP00109

Recipient:
Board of Regents of the Nevada System of Higher Education on Behalf of The University of Nevada, Reno

Principal Investigator:
John N. Louie
Telephone: (775) 784-4219 Fax: (775) 784-4165 louie@seismo.unr.edu
http://crack.seismo.unr.edu/louie

Title:
Estimation of Three-Dimensional Basin Geometry in Reno, Nevada from Waveform Inversion

Project Term:
April 30, 2016 — April 30, 2018

NEHRP Element(s):
IMW Element III.
Research on earthquake occurrence, physics, effects, impacts and risks.
Keywords: Site effects, Basin effects, Scenario modeling, Ground motions, Seismic zonation, Engineering seismology

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number **G16AP00109**. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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Estimation of Three-Dimensional Basin Geometry in Reno, Nevada from Waveform Inversion

John N. Louie
University of Nevada Seismological Laboratory, Reno, NV 89557
Telephone: (775) 784-4219 Fax: (775) 784-4165 louie@seismo.unr.edu
http://crack.seismo.unr.edu/louie

TECHNICAL ABSTRACT

The impacts of seismic shaking on urban basins have been in the news again this past year, driving the need for this NEHRP-funded research project. Construction projects for tall buildings in US West Coast cities have been delayed out of concerns that current design standards may not sufficiently account for the shaking amplification that occurs in geologic basins. Building codes in Nevada pertaining to seismic hazard use the USGS National Seismic Hazard Mapping Program (NSHMP), which does not include site or basin amplification factors. The NGA-West2 ground-motion prediction equation (GMPE) incorporates basin amplification factors homogeneously in one dimension, based on minimum depths to certain shear-velocity values (e.g., Z1.0, Z2.5) and on the geotechnical average velocity to 30 m depth (Vs30). We investigate whether such GMPEs may adequately predict amplifications recorded in the Reno-area urban basin of western Nevada by ANSS stations. We are quantifying and comparing basin amplification factors recorded from a series of local and regional events in and around the Reno-area basin. The focus of our analysis lies in the variation of amplification factor with spatially distributed source locations relative to the Reno-area urban basin. Northern Nevada Seismic Network ANSS broadband records we are examining include the: 2008 Mogul sequence; 2015 M4.3 Thomas Creek; and three 2015 M~5.5 Nine Mile Ranch events. Initial investigation is into peak ground velocity (PGV) ratios of basin over bedrock stations; leading to including other measures of shaking intensity such as H/V spectra and duration. We have generated 3D physics-based SW4 synthetic seismograms for these events that partially account for basin effects at relatively high frequencies of shaking up to 3.0 Hz, and we can examine how well the synthetic PGV ratios predict the recorded ratios. Some of the highest-frequency, most intensive SW4 computations were completed on the Amazon Web Services (AWS) cloud at minimal cost. Using the computational models, we perform sensitivity testing on the model through varying Vs30, basin shear velocity profiles, and incorporating deep volcanic sub-basins, as a first step toward basin-scale inversion. The sensitivity tests extend to comparisons of shaking and amplification up to 3 Hz frequency, for three different Reno-area basin models originating with the USGS, UNR, and Washoe County gravity measurements and modeling. We are working toward combining these varying gravity models of the basin together, and with constraints from geological data, ANSS recording inversions, and 1-3 Hz 3d modeling results into a community basin model. Initial results have been presented at regional and international conferences. Velocity and computational models and methods are posted publicly.

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University of Nevada Seismological Laboratory, Reno, NV 89557
Telephone: (775) 784-4219 Fax: (775) 784-4165 louie@seismo.unr.edu
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Introduction

The impacts of seismic shaking on urban basins have been in the news again this past year, driving the need for this NEHRP-funded research project. Construction projects for tall buildings in US West Coast cities have been delayed out of concerns that current design standards may not sufficiently account for the shaking amplification that occurs in geologic basins. Building codes in Nevada pertaining to seismic hazard use the USGS National Seismic Hazard Mapping Program (NSHMP), which does not include site or basin amplification factors. The NGA-West2 ground-motion prediction equation (GMPE; Boore and Atkinson, 2008; Chiou and Youngs, 2008; Campbell and Bozorgnia, 2008) incorporates basin amplification factors homogeneously in one dimension, based on minimum depths to certain shear-velocity values (e.g., Z1.0, Z2.5) and on the geotechnical average velocity to 30 m depth (Vs30).

An accurate understanding of the ground motions and their variability in the Reno-Carson City region from earthquakes is important to realistically quantify seismic hazard. Geologic evidence indicates the potential for large magnitude (M7-7.5) events occurring on local faults, such as the Genoa Fault, which could pose a severe risk to lives and property in this growing metropolitan area (e.g., dePolo et al., 1997). Fortunately, no large earthquakes have struck the region since it has become heavily populated. The Mogul/West Reno earthquake swarm of 2008 actually provided a few strong-motion records in limited areas of the city (Anderson et al., 2009), and vastly increased the number of records available from the urban basin. The 2015 M4.4 Thomas Creek earthquake, also within the basin (Hatch et al., 2016; Rodgers et al., 2016), and three regional 2016 M5.5 Nine Mile Ranch events provide additional recordings on broadband Northern Nevada Seismic Network ANSS stations in and around the basin (figs. 1, 2). Still, we must rely on scenario modeling to estimate ground motions from the expected damaging earthquakes.

We investigate whether such GMPEs may adequately predict amplifications recorded in the Reno-area urban basin of western Nevada by ANSS stations (figs. 1, 2). We are quantifying and comparing basin amplification factors recorded from a series of local and regional events in and around the Reno-area basin (Table 1). The focus of our analysis lies in the variation of amplification factor with spatially distributed source locations relative to the Reno-area urban basin.

Northern Nevada Seismic Network ANSS broadband records we are examining include: the 2008 Mogul sequence; the 2015 M4.3 Thomas Creek; and three 2015 M~5.5 Nine Mile Ranch events (Table 1). Initial investigation is into peak ground velocity (PGV) ratios of basin over bedrock stations; leading to including other measures of shaking intensity such as H/V spectra and duration.

Event	Magnitude	Date
Thomas Creek	Mw 4.4	2015-12-23
Mogul	Mw 4.9	2008-04-28
Nine Mile Ranch	3 ~M 5.5	2016-12-28

Table 1. Earthquake recordings examined and modeled in this project.

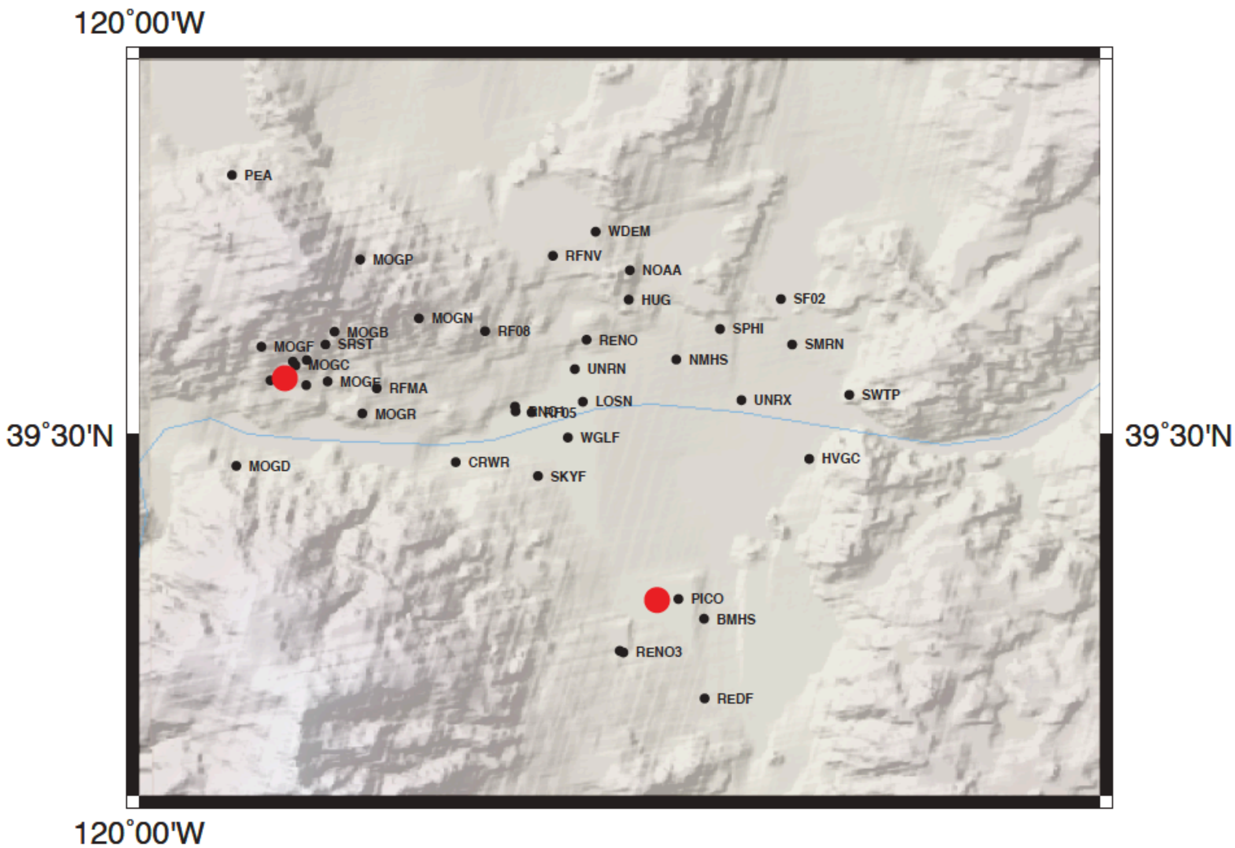

Figure 1. Shaded-relief map of the Reno-area basin and surroundings. Red dots locate the epicenters of the Mogul and Thomas Creek events (Table 1); black dots are Northern Nevada Seismic Network ANSS recording stations.

Methods and Results

Three-dimensional geological and geophysical models were built using Nevada ShakeZoning ModelAssembler (Flinchum et al., 2014). We generate 3D physics-based SW4 synthetic seismograms for the events of Table 1 that partially account for basin effects. Within the small model domain of fig. 1, we model to relatively high frequencies of shaking, up to 3.0 Hz. We examine how well the synthetic PGV ratios predict the recorded ratios. Using the computational models, we perform sensitivity testing on the model through varying Vs30, basin shear velocity profiles, and incorporating deep volcanic sub-basins, as a first step toward basin-scale inversion. Fig. 3 shows a shear-wave velocity map for the surface of one example model space, for the Nine Mile Ranch events.

The sensitivity tests extend to comparisons of shaking and amplification up to 3 Hz frequency, for three different Reno-area basin models originating with the USGS (Saltus and Jachens, 1995), UNR (Abbott and Louie, 2000), and Washoe County (Widmer et al., 2007; Cashman et al., 2012) gravity measurements and modeling. We are working toward combining these varying gravity models of the basin together into a community basin model, with constraints from: geological data; the Deep ReMi results of Pancha et al. (2017), Pancha and Pullammanappallil (2014), Pullammanappallil (2016), and Munger et al. (2016); ANSS recording inversions; and 1-3 Hz 3d modeling results. Initial results are posted publicly at http://crack.seismo.unr.edu/hazsurv/CME/data/?C=M;O=D .

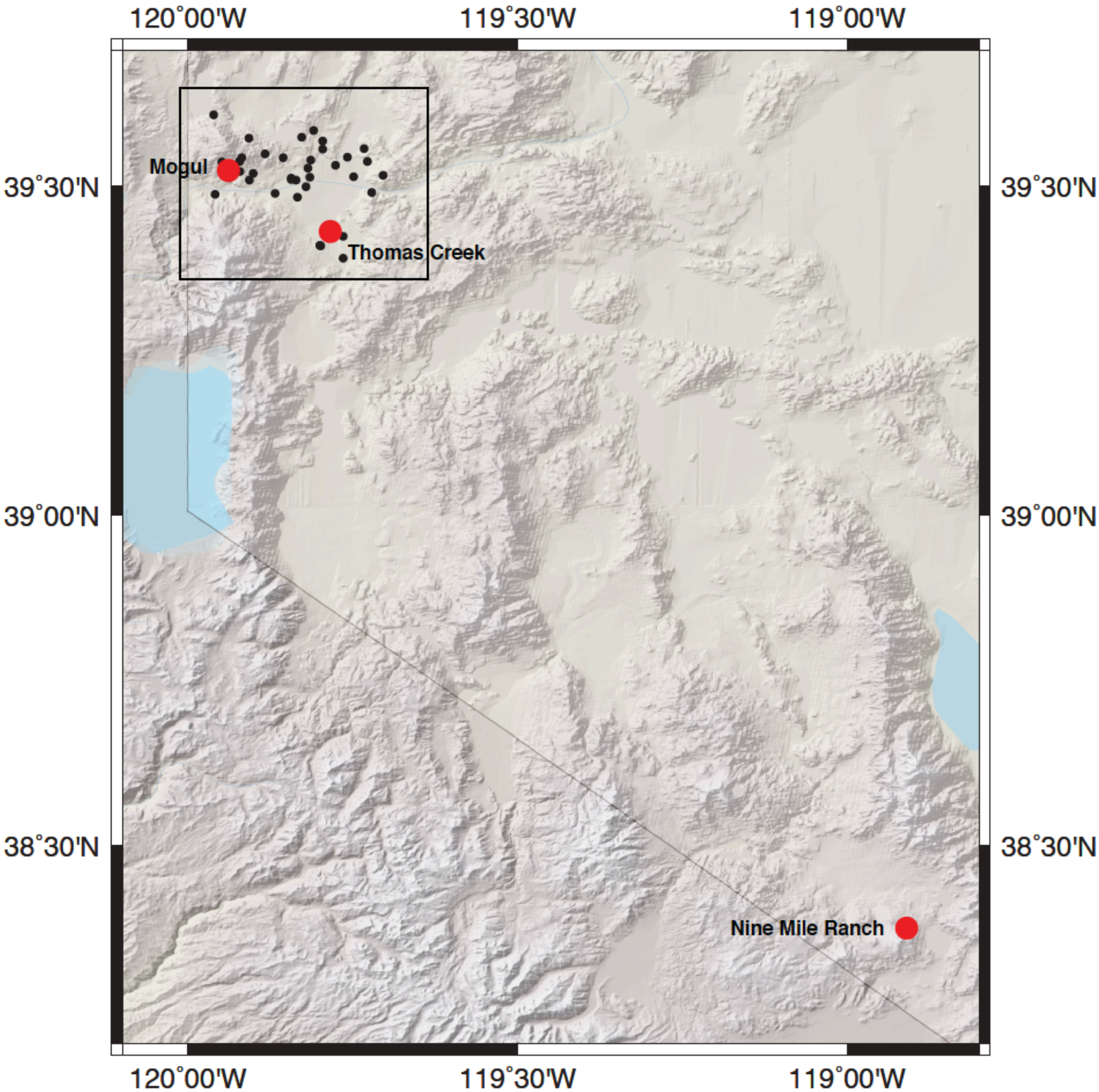

Figure 2. Shaded-relief map of part of western Nevada.. Red dots locate the epicenters of the Mogul, Thomas Creek, and Nine Mile Ranch events (Table 1); black dots are Northern Nevada Seismic Network ANSS recording stations in and near the Reno-area basin. Lake Tahoe is at left; Walker Lake at lower right.

For 3D computational modeling of earthquake ground motions, we used SW4 versions 1.1 through 2.01 (Sjögreen and Petersson, 2012; Petersson and Sjögreen, 2012; Petersson and Sjögreen, 2017; Petersson and Sjögreen, 2015; Petersson and Sjogreen, 2017) published under the GPL 2 license. All velocity models include a "geotechnical layer" at the surface based on Vs30 measurements (Scott et al., 2004; Pancha et al., 2012; Louie et al., 2013). Velocity and density properties within the basins in the model are derived from the kilometer-deep ReMi™ results of Pancha et al. (2017), Pancha and Pullammanappallil (2014), and Pullammanappallil (2016). The first Nine Mile Ranch event is modeled up to 1.0 Hz using the Abbott and Louie (2000) Reno-area basin model, with a 1D velocity model elsewhere (fig. 3). A second model variation was computed using the Abbott and Louie (2000) Reno-area basin thickness model with Saltus and Jachens (1995) basins elsewhere; to model the regional basins between the NMR source and Reno.

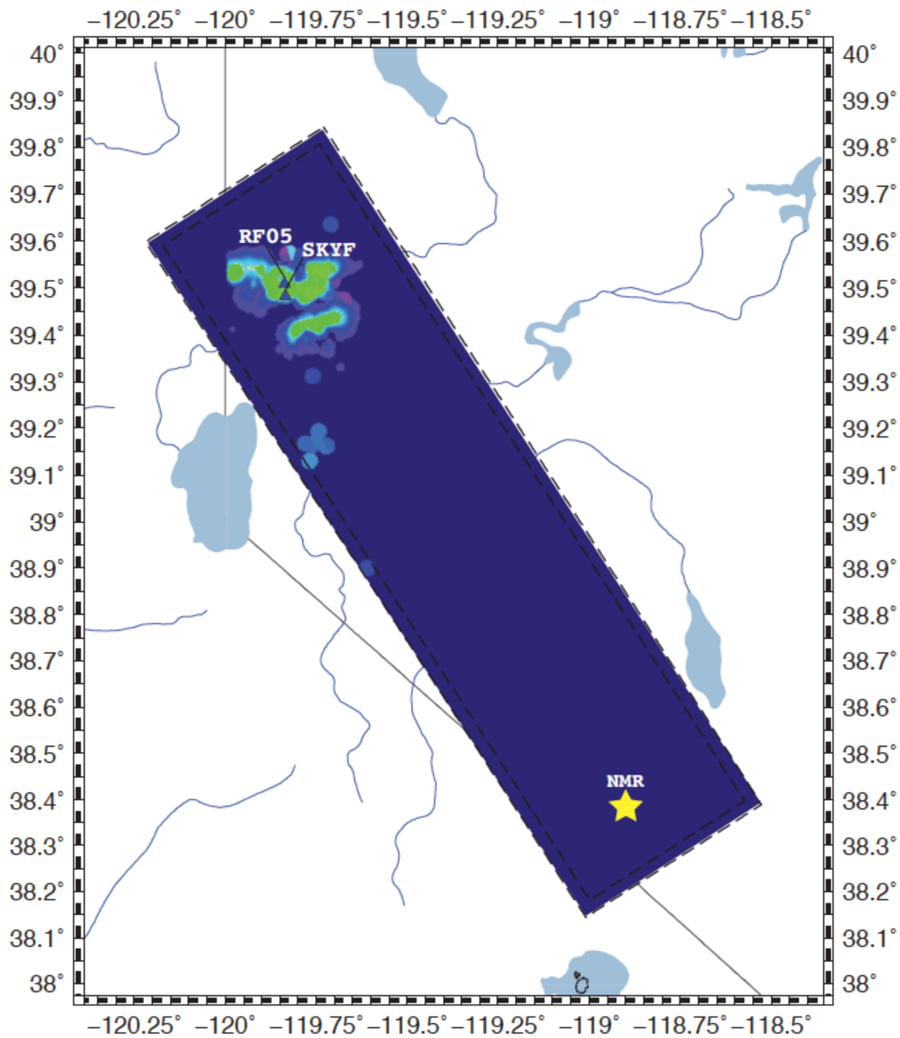

Figure 3. Map showing the regional SW4 modeling domain for 1.0 Hz computation of shaking in the Reno-area basin (upper left) from the three Nine Mile Ranch events (NMR). Colors on the model domain indicate surface shear velocity, with bedrock Vs > 1.0 km/s as blue, and warmer colors for Vs < 1.0 km/s in the Reno-area basin. This trial 3D velocity model excluded the many basins other than the Reno-area basin.

Three simulations of the Mogul event calculated up to 3 Hz are generated to test the three basin-depth models (Saltus and Jachens, 1995; Abbott and Louie, 2000; and Widmer et al., 2007 and Cashman et al., 2012), and compared to recorded ground motions. Mogul mainshock parameters location and moment magnitude are adapted from relocations (Ruhl et al., 2016). Peak vertical and horizontal ground velocity maps are calculated from the three Mogul simulations. PGV ratio maps are generated to understand the spatial variance of ground motion resulting from the three basin depth models (fig. 4).

The three Mogul simulations were computed on Amazon Web Services on a 40 km x 40 km x 30 km grid with two mesh refinement layers and 25 meter grid spacing at the surface for a total of 310 million grid points. Minimum velocity was about 600 m/s. Each Mogul simulation cost about $300 on AWS, funded by the Nevada Seismological Laboratory.

Amplification ratios in the Reno Basin were computed using waveform data recorded on the Nevada Seismological Laboratory's Northern Nevada Seismic Network, part of the Advanced National Seismic System. The waveform data used were recordings of the three events in Table 1 by the stations in figs. 1 and 2.

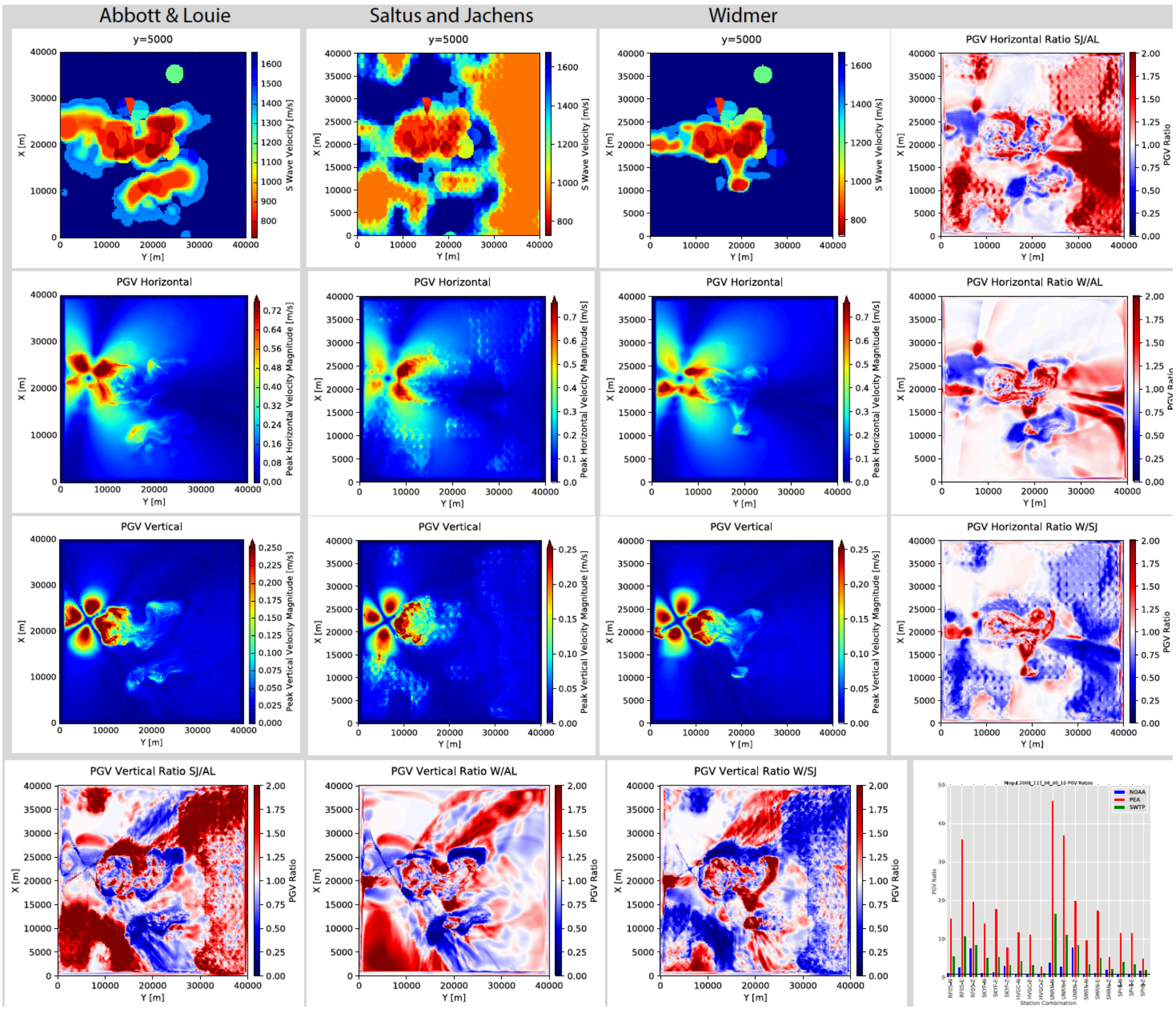

Figure 4. 3D computations of shaking from the Mogul earthquake to 3.0 Hz using SW4 on AWS. Simulations used one of three alternative Reno-area basin models: SJ (Saltus and Jachens, 1995); AL (Abbott and Louie, 2000); or W (Widmer et al., 2007; Cashman et al., 2012). The top row shows Vs maps for each model; the second row horizontal peak ground velocity (PGV) maps; and the third row vertical PGV maps. The right edge has example horizontal PGV-ratio maps; the bottom edge is example vertical PGV-ratio maps. Very bottom right is a chart comparing computed PGV ratios at basin stations, when dividing by the computed PGV at rock station NOAA (blue), PEA (red), or SWTP (green).

Peak ground velocity ratios of basin over bedrock stations are calculated from recorded data and synthetic seismograms. PGV ratios at basin stations are calculated using various rock stations as the denominator, and distance-corrected by 1/r. Figure 4 at the lower right shows synthetic Mogul-source PGV ratios at each basin station, for each of three choices of bedrock station in the denominator (figs. 1, 2): NOAA on the north edge of the Reno-area basin; PEA at the summit of Peavine Mountain northwest of the basin; and SWTP at the eastern edge of the basin. All of these local "rock" stations sit on Tertiary volcanic flows that Saltus and Jachens (1995) considered "volcanic basin" rocks. They all thus sit on complex geology, with complex site conditions. The same is true of the REDF station at the south end of the basin, which sits on a complex geothermal field of fumaroles, hot springs, and phreatic explosion craters.

Figure 5 shows basin/bedrock PGV ratios from 1-3 Hz recordings of the Thomas Creek earthquake. Some ratios are extreme, particularly when dividing by the PEA station's recordings. Aside from the high variability of basin amplifications depending on which bedrock station is used to normalize, there is additional variance depending on which station component is examined. From the Thomas Creek shaking records at 1-3 Hz, basin stations appear to have experienced amplifications of a factor of 4.0 at minimum, and potentially much larger. This degree of amplification is far above the predictions of the NGA-West2 GMPEs.

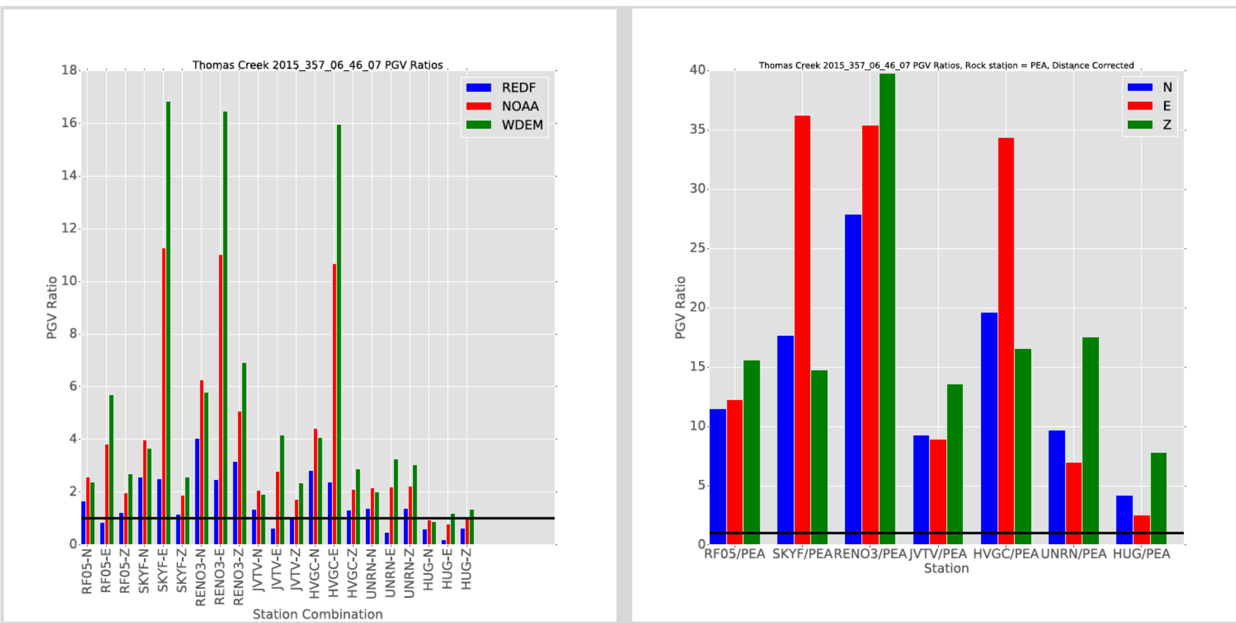

Figure 5. (*left*) Recorded PGV ratios at 1-3 Hz for the Thomas Creek event, for the N, E, and Z components of stations in the Reno-area basin, for each of three different possible bedrock denominator stations REDF, NOAA, and WDEM. (*right*) Averaged horizontal PGV ratios of basin stations recording the Thomas Creek event, relative to the PEA station. A ratio of 1.0 is at the horizontal black line.

Figure 6 shows 0.2-1.0 Hz basin amplifications recorded in the Reno-area basin from three Nine Mile Ranch earthquakes, at about 100 km distance. Basin amplifications are overall much lower than recorded for the Thomas Creek event, which was in the basin. The maximum amplification is a factor of 3.0, perhaps not out of line with the NGA-West2 GMPEs. Yet the per-component amplifications are unexpectedly variable between the three M~5.5 events, despite the events all occurring within a few kilometers of each other, with very similar focal mechanisms and other source parameters.

Figure 7 shows computed 0.2-1.0 Hz basin amplifications for a model of the initial Nine Mile Ranch earthquake. The two rows compare velocity models, with the upper row having only the Reno-area basin, and the lower row having all the basins in the source area and in between Nine Mile Ranch and Reno. Comparing both with the top row of fig. 6, the Reno-only basin model appears to predict basin amplifications larger than those recorded, but broadly similar. Unexpectedly, the more realistic all-basin model of the lower row is predicting de-amplification within the Reno basin, at least at 0.2-1.0 Hz frequency.

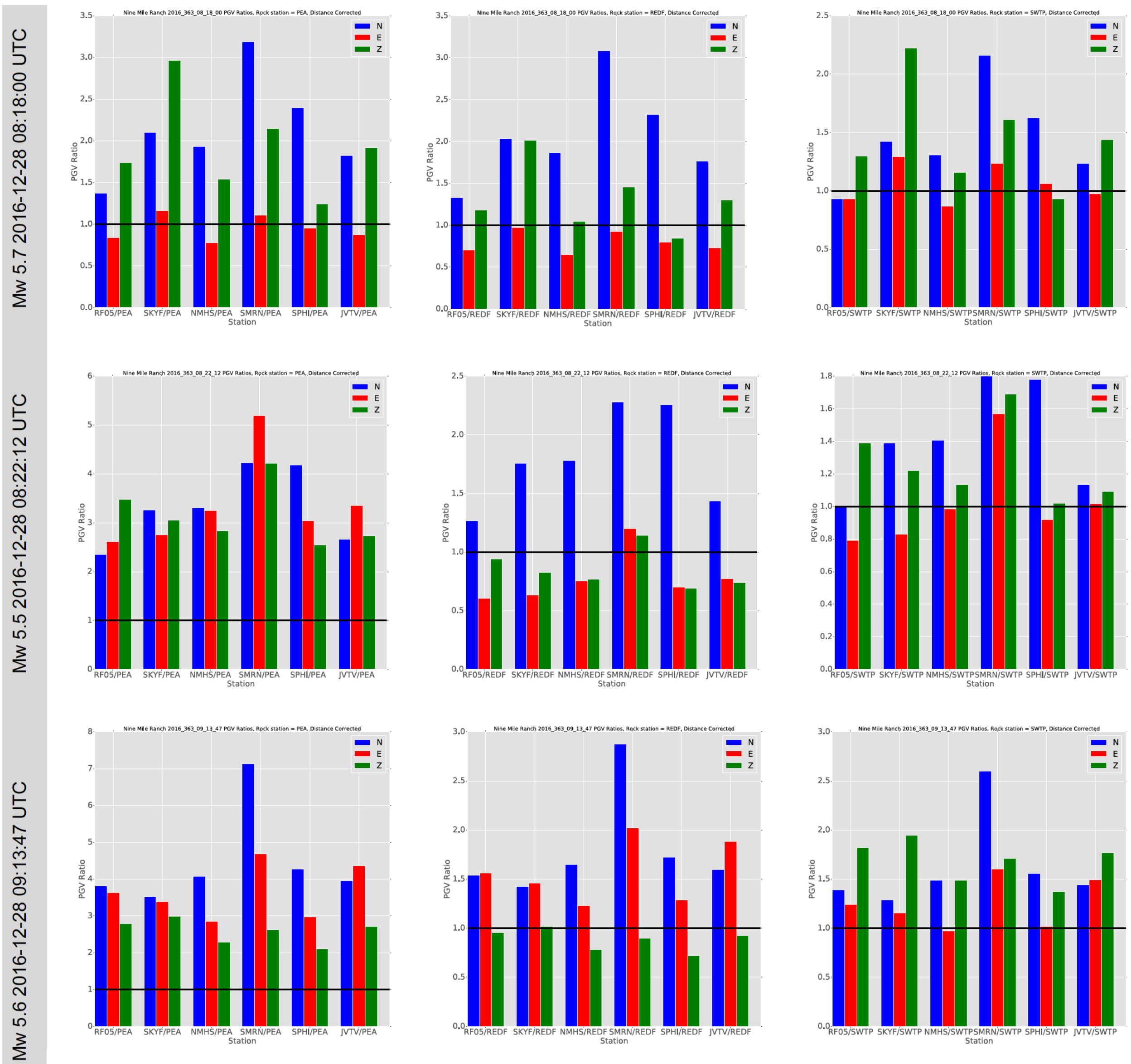

Figure 6. Recorded PGV ratios between 0.2-1 Hz of basin stations over bedrock stations, from the three Nine Mile Ranch earthquakes 100 km southwest of the Reno-area basin. A ratio of 1.0 is at the horizontal black line. The bar colors show individual N-, E-, and Z-component PGV ratios.

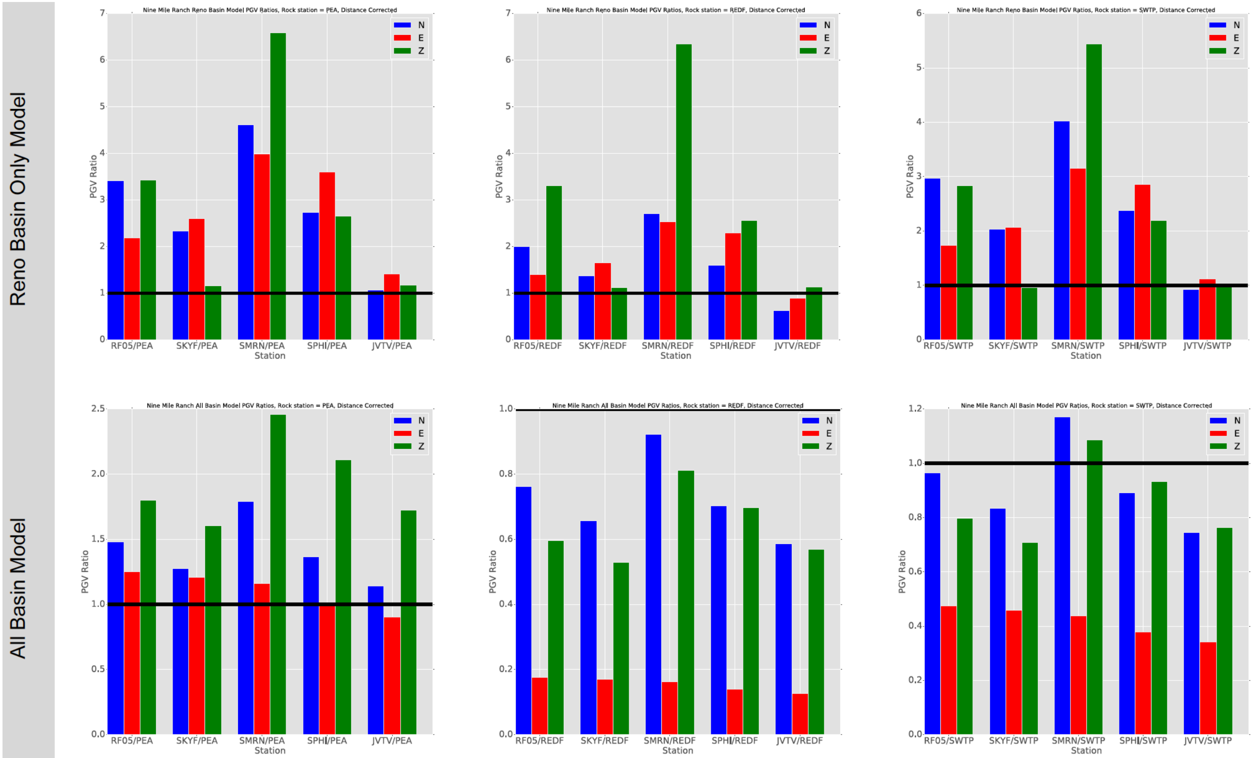

Figure 7. Synthetic PGV ratios between 0.2-1 Hz of basin stations over bedrock stations, modeling the initial Nine Mile Ranch earthquake 100 km southwest of the Reno-area basin. The upper row is from the model of fig. 3, including only the Reno-area basin in the velocity model, and having a 1D bedrock velocity model elsewhere including the Nine Mile Ranch area. The lower row is computed from a velocity model including all Abbot and Louie (2000) and Saltus and Jachens (1995) basins within the model area of fig. 3. Compare each row here to the top row of fig. 6. A ratio of 1.0 is at the horizontal black line. The bar colors show individual N-, E-, and Z-component PGV ratios.

Figure 8 plots comparisons of recorded and synthetic PGV at 0.2-1 Hz from the Nine Mile Ranch events, by station and component. Discounting the unexpectedly low ground motions predicted by the supposedly more realistic “all basins” model, computed ground motions appear to match the recorded to within a factor of about 2.0. Given the similarly unexpected variance recorded in ground motions between the three very similar Nine Mile Ranch events, that factor of two mismatch may be irreducible, at least in this frequency range.

Figure 9 shows example full-wave seismograms computed to 3 Hz frequency at a few stations, along with the corresponding recorded trace in black, for the Mogul earthquake. For each of the three stations, we computed synthetics for each of the three different Reno-area basin models. The shallow-basin station HVGC recorded a far longer duration of shaking than any of the basin models could predict, and modeled peak motions are two or three times too large. For the stations outside the basin the waveform match is very good, though computed peak amplitudes are still much too high.

Figure 10 plots PGVs recorded from the Nine Mile Ranch sequence versus basin thickness and Vs30. The GMPEs include ground-motion dependencies on these station properties. The time-averaged shear-wave velocity to 30 m depth Vs30 should lead to higher ground motions as it decreases. The depth at which shear-wave velocity first reaches 1.0 km/s, Z1.0, should lead to higher ground motions as it increases. In the Reno-area basin, Pancha et al. (2017) showed that the Abbott and Louie (2000) basin thicknesses are reasonably representative of Z1.0. Both the Z1.0 and the Vs30 ground-motion trends may be visible in fig. 10, but only for the minimum motions at each station, from NMR event 3. The maximum motions appear uncorrelated with either property. As well, the ground-motion variance at each station appears to be larger than the systematic variances due to the changes in either Vs30 or Z1.0.

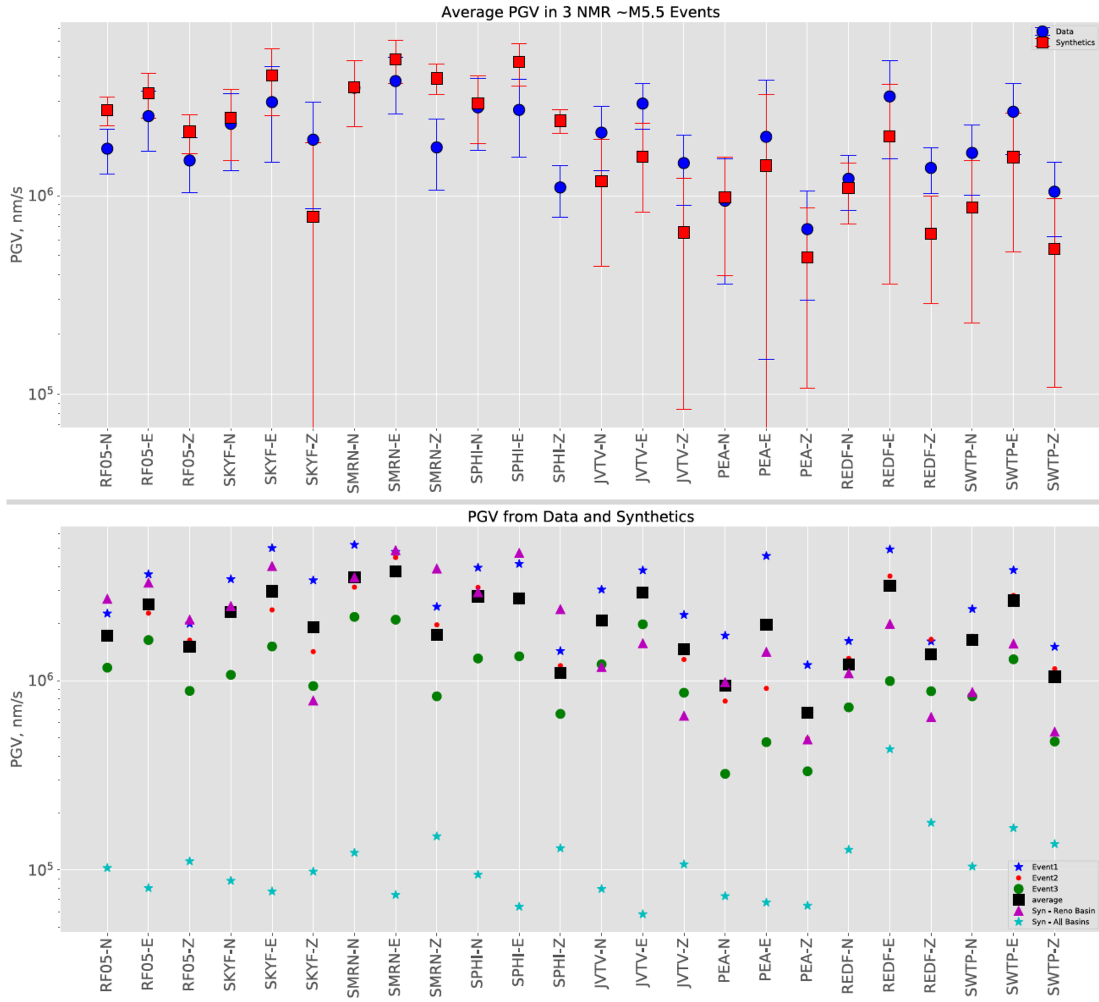

Figure 8. Comparisons of recorded and synthetic PGV at 0.2-1 Hz from the Nine Mile Ranch events, by station and component. Stations RF05, SKYF, SMRN, SPHI, and JVTV on the left are within the Reno-area basin; stations PEA, REDF, and SWTP are on Tertiary volcanics outside the basin.

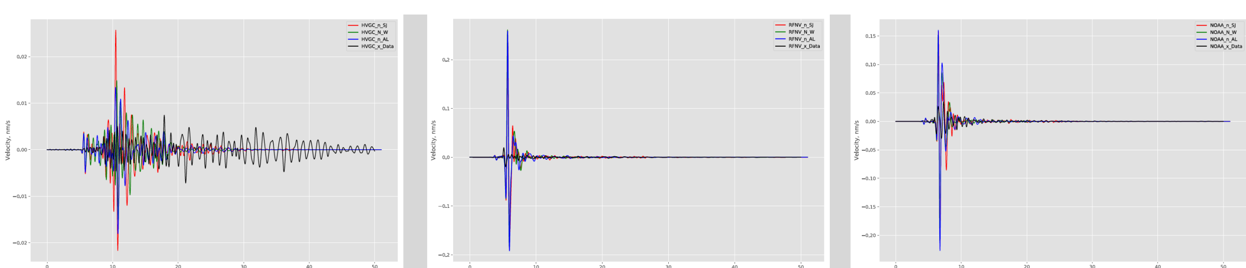

Figure 9. Example synthetic seismograms computed up to 3 Hz for the Mogul event; computed through three different Reno-area basin models; at shallow-basin station HVGC and bedrock stations RFNV and NOAA. Recorded data trace is black; SJ model synthetic (Saltus and Jachens, 1995) is red; W model (Widmer et al., 2007; Cashman et al., 2012) is green; AL model (Abbott and Louie, 2000) is blue.

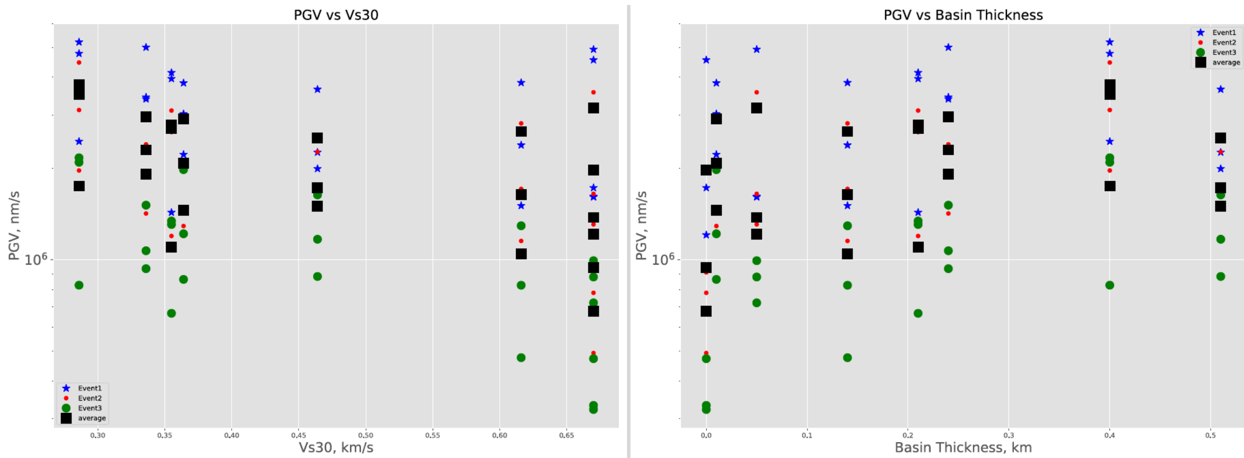

Figure 10. PGV recorded at Reno stations for the Nine Mile Ranch events, plotted against station Vs30 and basin thickness or Z1.0.

Horizontal over vertical spectral ratios are calculated for the station recordings according to Nakamura (1989). The fundamental frequency is assumed to be related to the depth-to-bedrock by f_0 = Vs/4/Z1.0 (Dobry et al., 2000). Figure 11 shows spectral-ratio analysis of few station records from two earthquakes. The vertical lines denote the frequencies that the H/V spectral peaks should have if they originate due to vertical resonance in a basin with the thickness according to each of the three Reno-area basin models. For the basin station UNRN, the spectral ratio does not appear valid to low enough frequencies to make any correlation. For the bedrock station NOAA, a peak appears but seems to move around in frequency between the two earthquakes. The peak is thus not clearly a site effect, and may be a source effect.

In addition to testing the three existing Reno-area basin models, we are beginning to integrate apply geological and geophysical constraints in an effort to develop a useful Community Velocity Model (CVM). Abbott and Louie (2000) provide one basic gravimetric analysis of the Reno-area basin. We have sought to improve upon this model using new statistical approaches. There were several steps involved with this process. Abbott and Louie gravimetric data was processed assuming a basin model, as a result the points are only valid in geologic basins. Reanalyzing the original data with reference to the State geologic map (Stewart and Carlson, 1978) allowed us to include additional, shallow basins occurring at high elevations surrounding Reno. These depths were then converted to an elevation using a DEM of Washoe and Storey counties (USGS NED, 2013). A new surface was also added in the southern part of the extent where the surface of the Virginia range is essentially bedrock. This new point cloud was then interpolated using an empirical Bayesian kriging algorithm with an exponential (power) semivariogram as implemented in ArcGIS 10.5.1. As a result, in fig. 12 we have significantly improved upon the Abbott and Louie surface, especially in areas of high topographic relief in the southwestern portions of our target area. The next part of this process will involve re-analysis and reprocessing of the non-basin units present in the Virginia Range to the east, hopefully resulting in a surface better suited to future three-dimensional Reno-area basin models.

Conclusions

- High H/V spectral ratios at NOAA and low PGV ratios when NOAA is the treated as a rock station suggest the presence of a basin at NOAA, below Tertiary andesite. The Widmer model shows a shallow basin at NOAA, while the Abbott and Louie and Saltus and Jachens treat NOAA as bedrock.
- Mogul synthetic seismograms to 3 Hz are higher in peak amplitude than observed ground motions. Mismatch in the seismograms can be the product of the source model, 3D geologic model, or the lack of topography in the simulations.

- Nine Mile Ranch simulations indicate that basin amplification is sensitive to the global minimum shear velocity. While computing higher frequencies becomes computationally expensive at lower velocities, basin effects are not modeled correctly when shallow low velocities are excluded.
- There is no clear correlation between PGV and Vs30 or basin thickness.

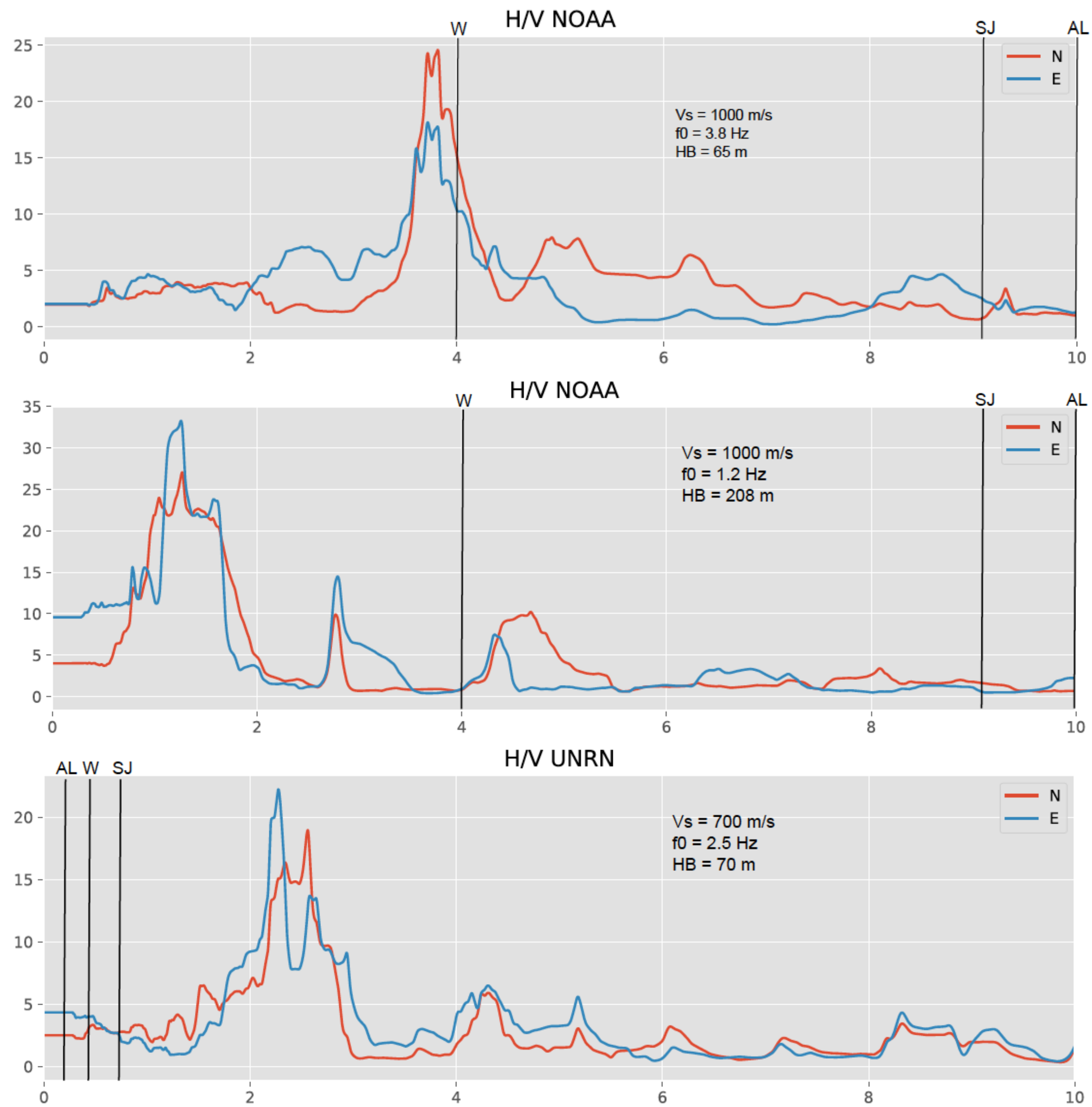

Figure 11. H/V spectral ratio analyses of N and E components of three recordings. NOAA is a bedrock station; UNRN is a basin station. Upper is analysis of a NOAA station record from the Thomas Creek earthquake; middle and lower are records of the Nine Mile Ranch events. Black vertical lines mark frequencies where the H/V ratio should show a peak, according to the basin depths at that station as estimated by SJ (Saltus and Jachens, 1995); W (Widmer et al., 2007; Cashman et al., 2012); and AL (Abbott and Louie, 2000).

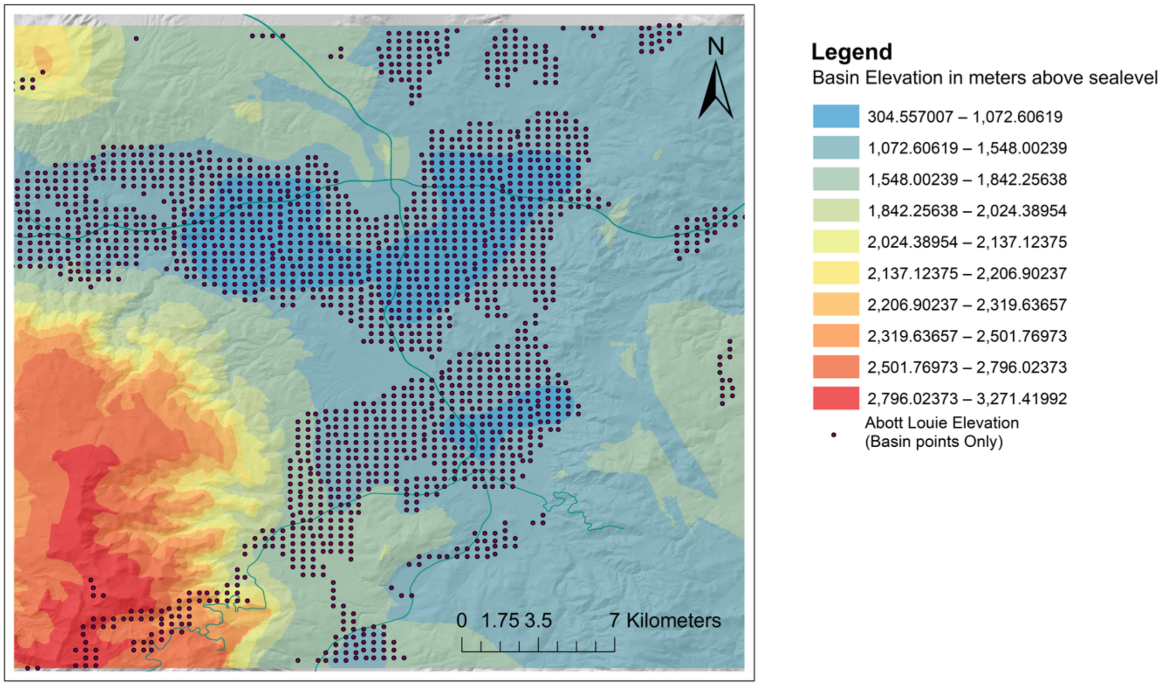

Figure 12. Newly developed draft elevation map of the Reno-area basin-floor elevation. Available for download from http://crack.seismo.unr.edu/hazsurv/CME/data/Reno-Abbott+Louie-kriged-30m-basin-elev.asc, 22 Mb ascii text file.

Acknowledgements

Nevada ShakeZoning software development, data collection, and research were partly supported by the U.S. Geological Survey (USGS), Department of the Interior; under USGS award numbers 07HQGR0029, 08HQGR0015, 08HQGR0046, G09AP00050, G09AP00051, G10AP00002, and G16AP00109 to Louie and others, and awards G11AP20022, G12AP20026, G14AP00020, and G15AP00055 to Optim. The Northern Nevada Seismic Network is supported under USGS award G10AC0090, and the Western Great Basin Seismic Network Operations are supported under USGS award number G10AC0090. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government. Richard Saltus and Bob Jachens of the USGS kindly made their basin-thickness results available to us. For maintaining and distributing SW4 software versions 1.1 through 2.01, we thank the Computational Infrastructure for Geodynamics (http://geodynamics.org), which is funded by the National Science Foundation under awards EAR-0949446 and EAR-1550901.

Publications and Presentations Partly Supported Through This Grant

(UNR students noted with “*”.)

J. Louie, Pancha, A., Pullammanappallil, S., and West*, L. T., 2018, Clark County Earthquake Parcel Map Vs30 effects on predictions of shaking for Las Vegas (paper 1477): Proceedings of the 11th National Conference in Earthquake Engineering, Earthquake Engineering Research Institute, Los Angeles, Calif., 5 pp. http://crack.seismo.unr.edu/ftp/pub/louie/papers/11NCEE-001477.pdf

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